Volume segmentation algorithms

Václav Krajíček

Department of Software and Computer Science Education
Faculty of Mathematics and Physics
Charles University

MFF UK
Prague

Outline

- Definition
- Data
- Methods classification
- Algorithms
- Examples
- Conclusion

Segmentation

- Definition

$$S : I \rightarrow R \qquad\qquad I\ image\ ,\ R = \{1, \ldots, n\}$$

- Alternatively

$$\bigcup_{i=1}^{n} R_i = I$$

$$R_i\ is\ connected$$

$$R_i \cap R_j = \emptyset \quad \forall_{i,j} \quad i \neq j$$

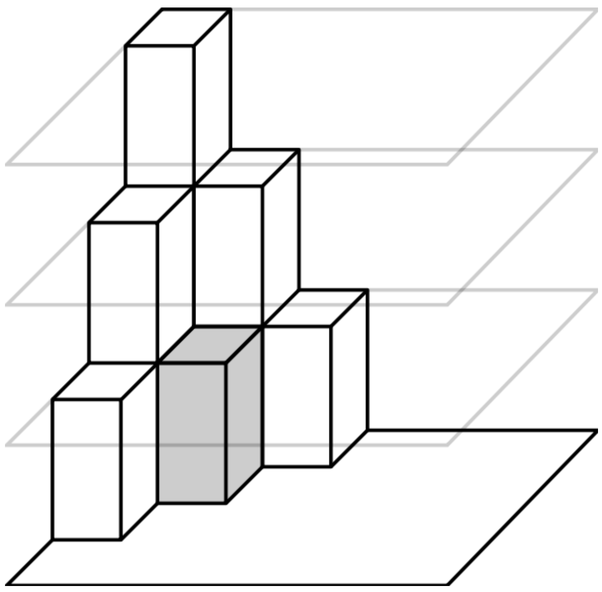
- Background/Foreground
- Many segments → over-segmentation
- Regions, surface, lines

Applications

- Volume measurement
- Visualization improvement
  - Removing unimportant, uninteresting parts
- Early step of image understanding
  - Classification of segments
- Dual to image registration
  - Better registration ↔ Better segmentation
- Information reduction
  - Compression algorithms
- There is no ideal algorithm

Data

- Raster image
  - Matrix of picture elements
  - Digital image theory
  - High frequency (edges) vs. Low frequency (regions)
- **<u>Volumetric data</u>**
  - Volume elements
  - Edges → Border surfaces
- Vector data
  - Meshes
- Multidimensional data
  - Clustering



Methods classification

- Edge based
  - *"An edge separates two regions"*
  - Edge in 3D?
  - Image enhancement & Edge extraction algorithms
    - Filtering
- Region based
  - *"Region is a continuous set of similar pixels"*
  - Homogeneity criterion

Image information

- Noise
  - Everytime & Everywhere & Everyscale
  - Different characteristics
- Decision about element's regions based on
  - Intensity
    - Global methods, global information
  - Intensity & position
    - Local methods, local information
  - Intensity & position & region shape
    - Methods with prior information

Speed of segmentation

- Real-time
  - Simple and rough methods
- Interactive
  - User assistance
- Off-line
  - Parallelization
  - Multiple phases, scales
  - Combination of different algorithms

Autonomy

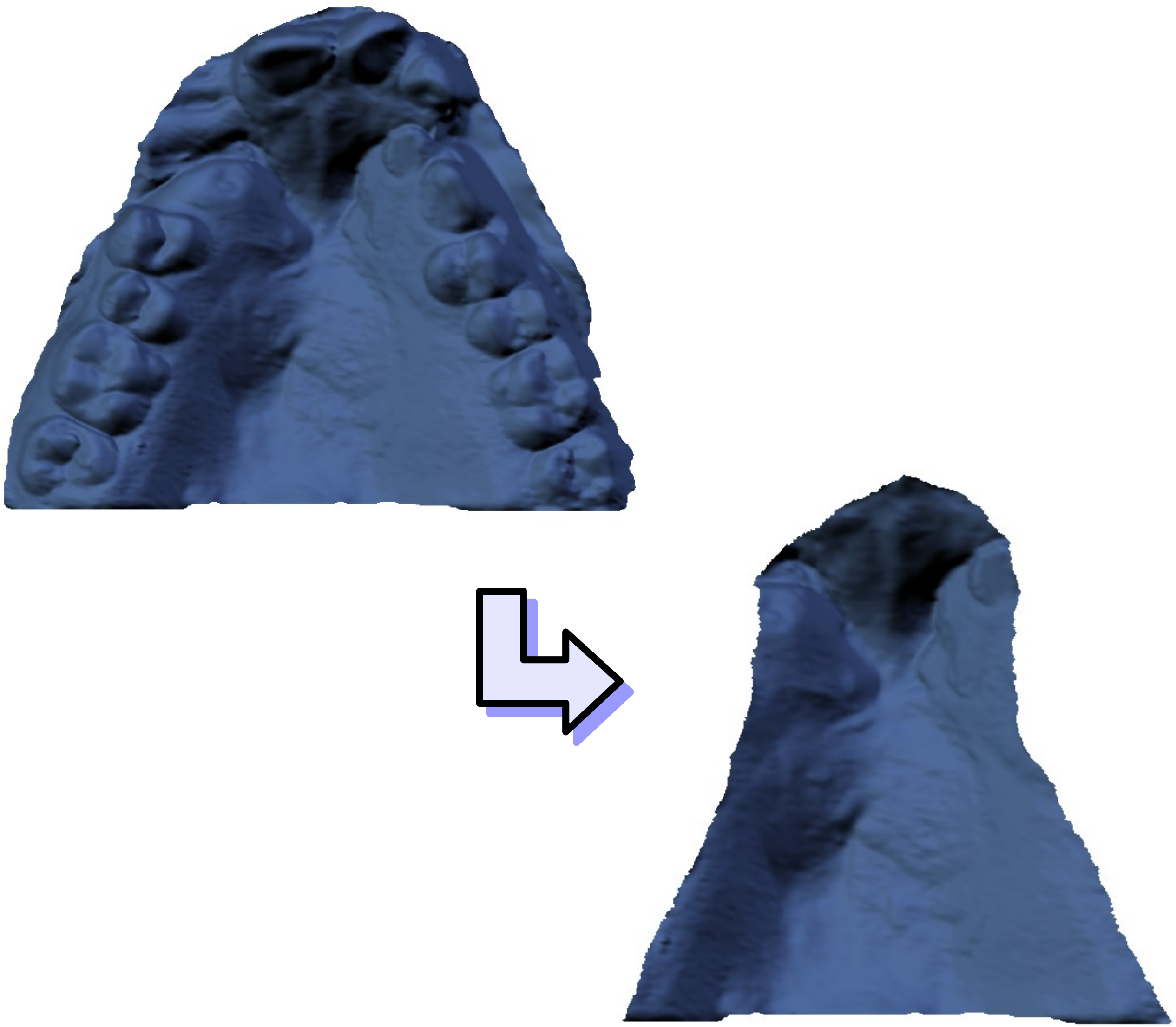
- Manual
  - Tedious user interaction
- Semi – automatic
  - Parameter tweaking
  - Initialization (position, first approximation)
- Interactive
  - Continuous interaction, acknowledgement
- Automatic
  - Fully autonomous
  - Less important part of production or QA process
  - Reliable

Examples

- Automatic
  - Palatum
- Semiautomatic
  - Kidneys
  - Cranium
- Interactive
  - Hip joint

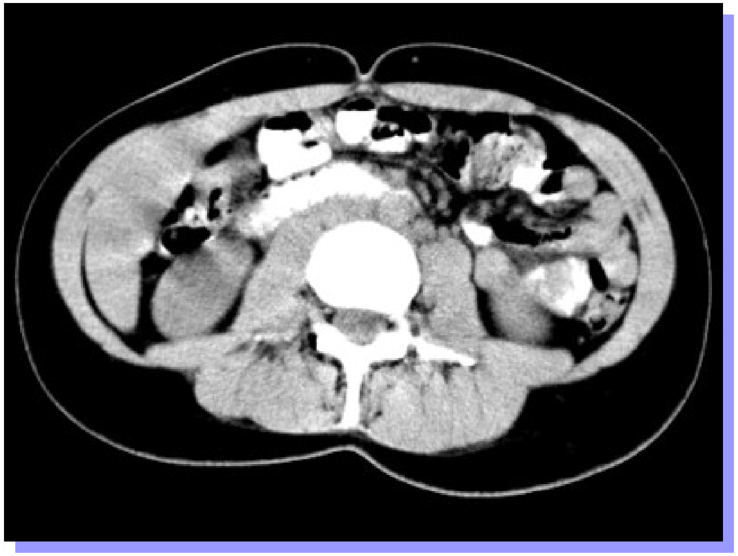
Examples

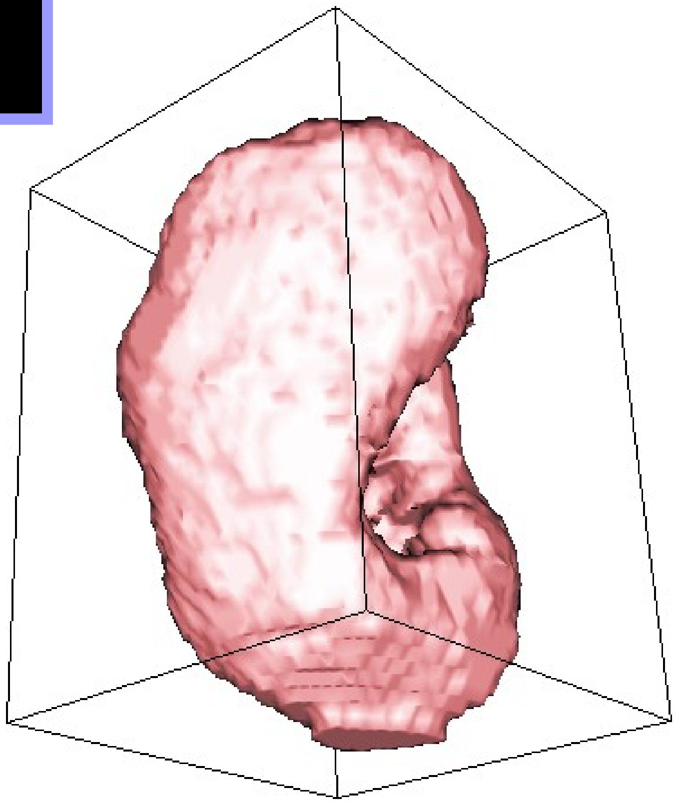
- Automatic
  - **Palatum**
- Semiautomatic
  - Kidneys
  - Cranium
- Interactive
  - Hip joint



Examples

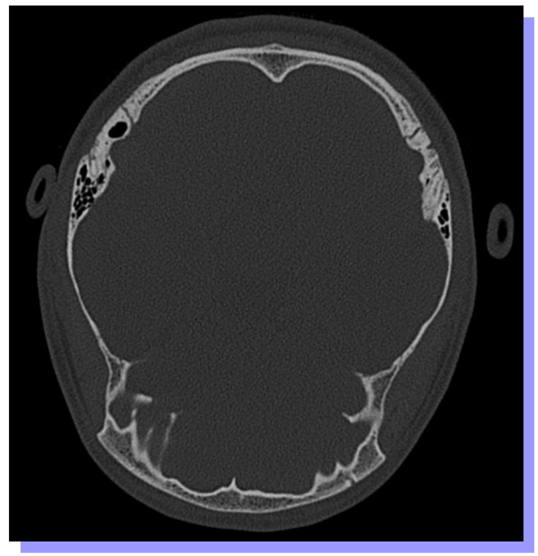
- Automatic
  - Palatum
- Semiautomatic
  - **Kidneys**
  - Cranium
- Interactive
  - Hip joint

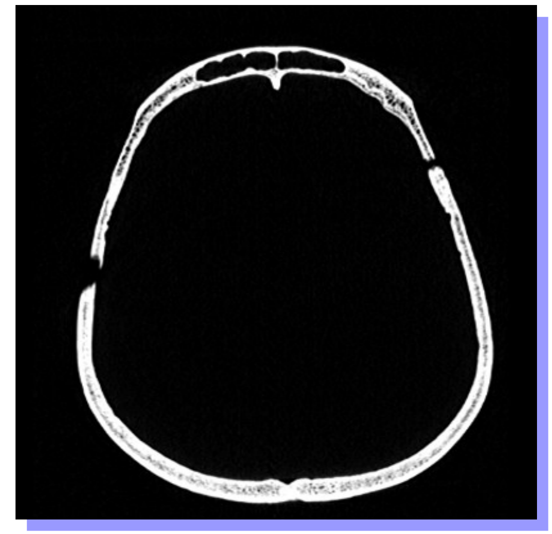


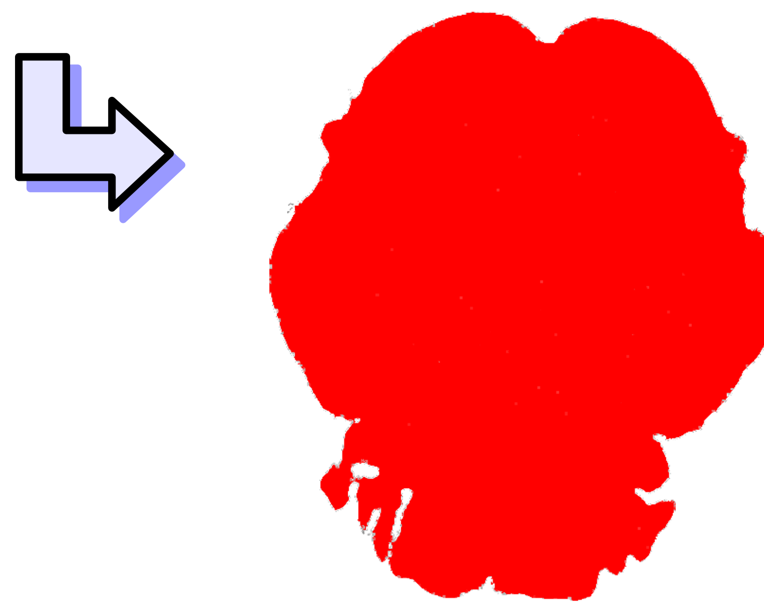


Examples

- Automatic
  - Palatum
- Semiautomatic
  - Kidneys
  - **Cranium**
- Interactive
  - Hip joint

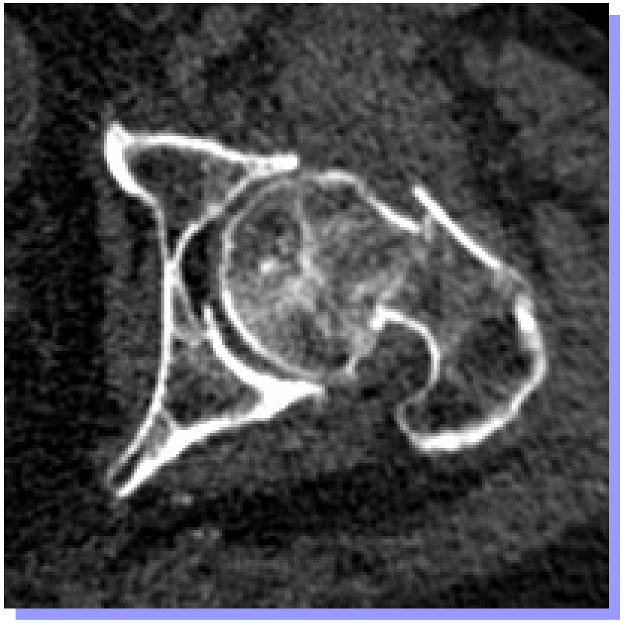


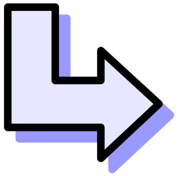




Examples

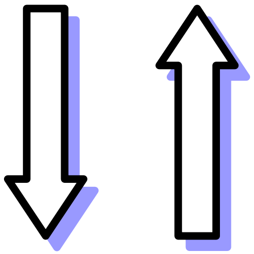
- Automatic
  - Palatum
- Semiautomatic
  - Kidneys
  - Cranium
- Interactive
  - **Hip joint**





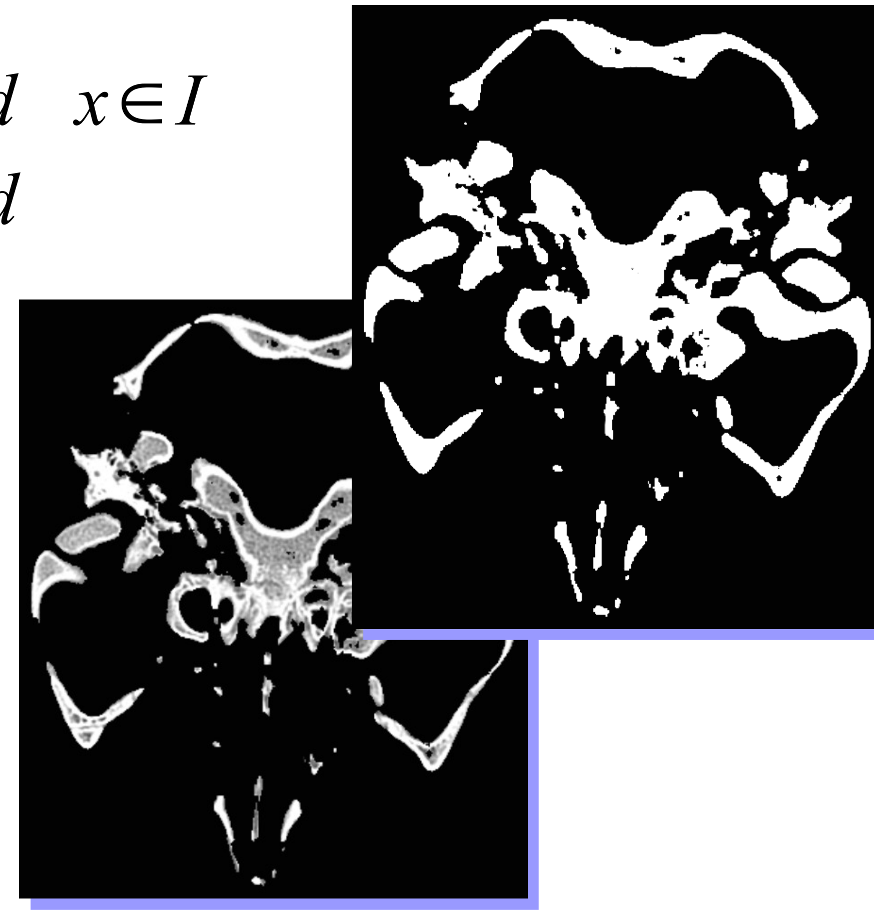
Segmentation pipeline

- Complicated algorithms
- Preprocessing
  - Image enhancement
- Scaling
  - Information reduction
  - Speedup
- Rough segmentation
- Segmentation refinement
- Segmentation enhancement
  - Isolated pixels removal, Holes filling, Morphological operations - erosion/dilatation/thinning/...



Thresholding

$$S(x)=\begin{cases} r_1 & \text{if } x < threshold \quad x \in I \\ r_2 & \text{if } x \geq threshold \end{cases}$$



- Frequently used
  - Simple, Manual
- Global method
  - Localized methods exist
- Automatic
  - Histogram based, Statistics
  - Sezgin & Sankur: Survey, 2004, 40 methods
- Multiple regions – multiple thresholds

Thresholding algorithms

- Simple algorithm

1) Initial threshold T0

$$m_i = \frac{1}{\|M_i\|} \sum_{x \in M_i} I(x)$$

2) Means of two groups

3) New threshold

$$T_t = \frac{1}{2}(m_1 + m_2)$$

4) Repeat from 2. until T changes

- Otsu's algorithm

1) Normalized histogram

2) Cumulative sums,means

$$P_i = \sum_{k_{i-1}}^{k_i} p_i$$

$$m_i = \sum_{k_{i-1}}^{k_i} jP(j/C_i)$$

3) Between-class variance

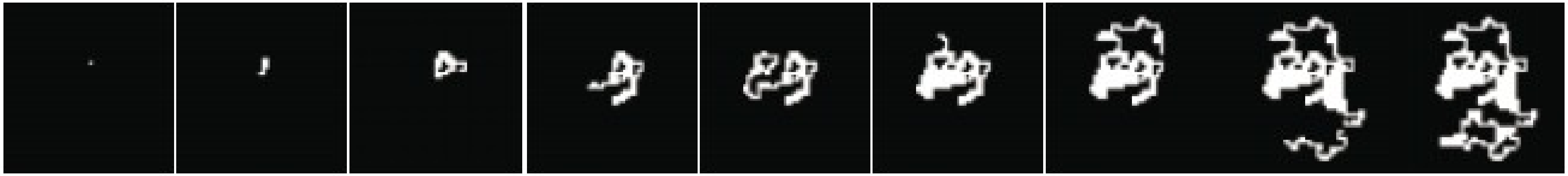
$$\sigma_B^2 = P_1(m_1 - m_G)^2 + P_2(m_2 - m_G)^2$$

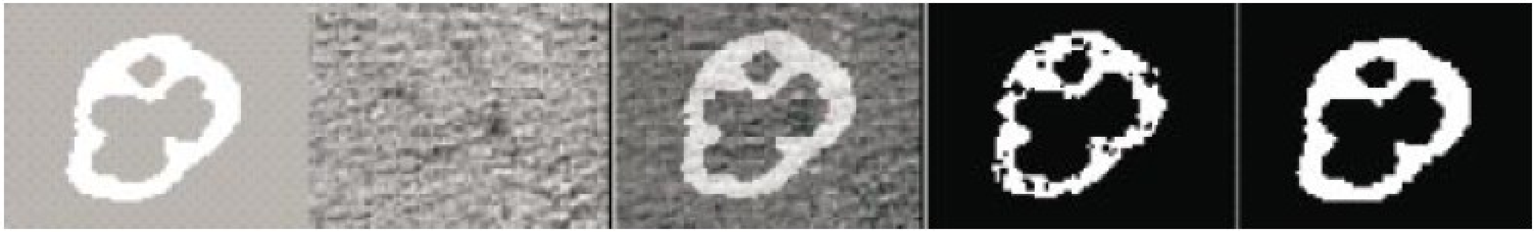
4) Maximize between class variance

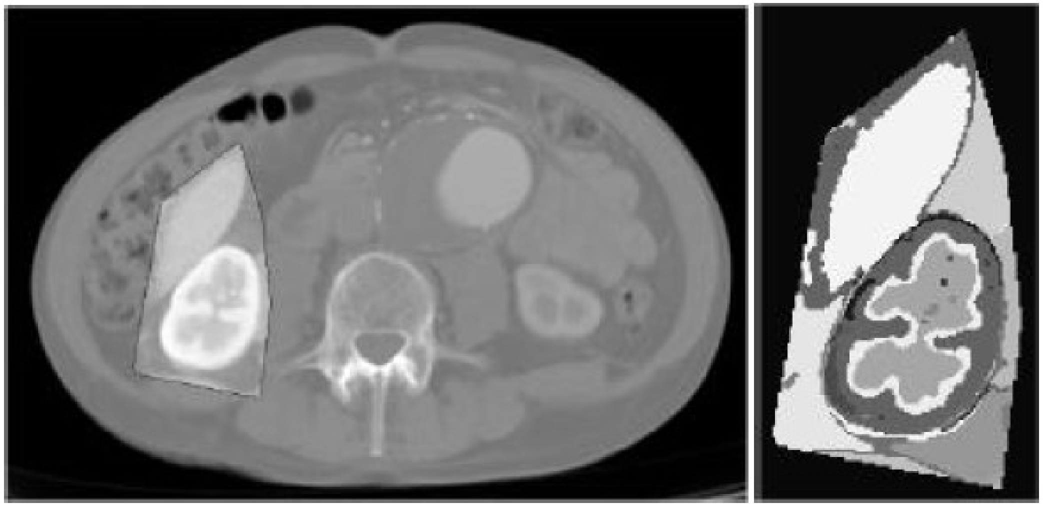
Region growing

- Similar to flood fill algorithm
  - seed(s) initialization – manual/automatic
  - one adjacent element per step
- Propagation depends on homogeneity criterion
  - Involves tresholds
- Variations
  - Adaptive homogeneity, Pohle 2001
  - Sphere of elements in one step, Fiorentini 2001

Region growing - example







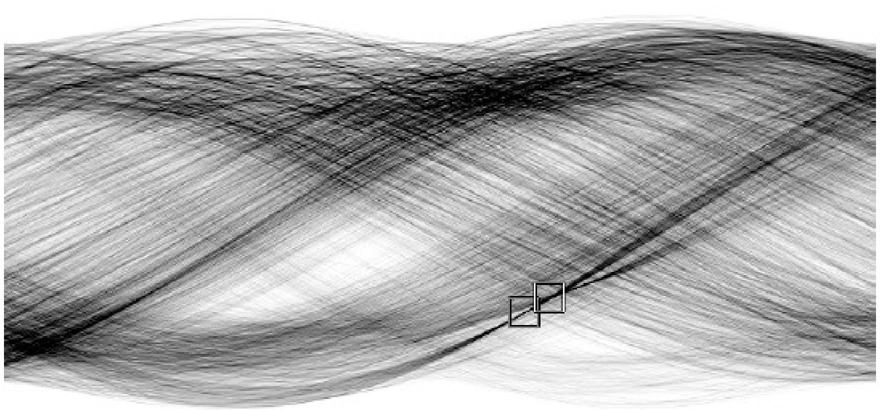
Splitting & Merging

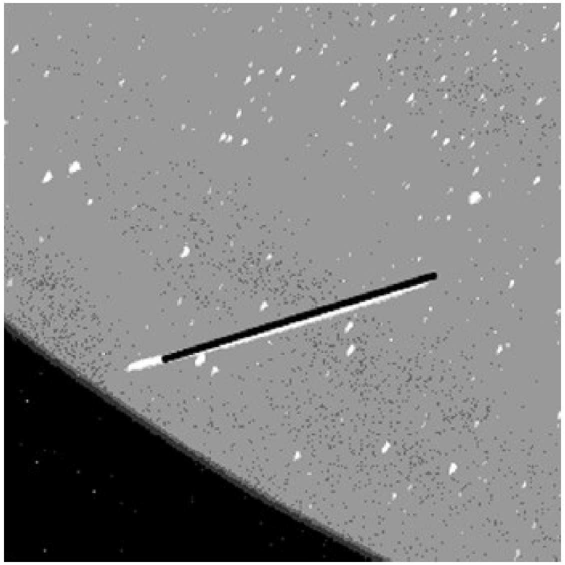
- Region based technique
- Unary predicate Q which is
  - TRUE if the parameter is likely to be region of segmentation
  - FALSE otherwise
- Image is recursively divided into quadrants
  - Splitting as long as Q is FALSE
  - Merging as long as Q is TRUE
- Various modification of the scheme

Hough transformation

- Edge based technique
- Connect several edge pixels to lines/curves
- “Which pixels form a line/curve?”
- Dual idea (lines example)
  - Each pixel possibly belongs to infinite number of lines
  - Which line has the most pixels?
  - Space of all lines → discretization → accumulator
    - Angle and shift
- Extendable to arbitrary dimension/shape
  - Computationally expensive

Hough transformation

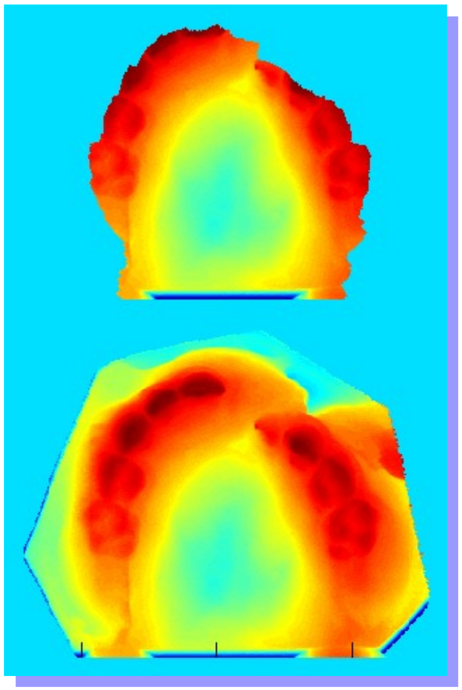


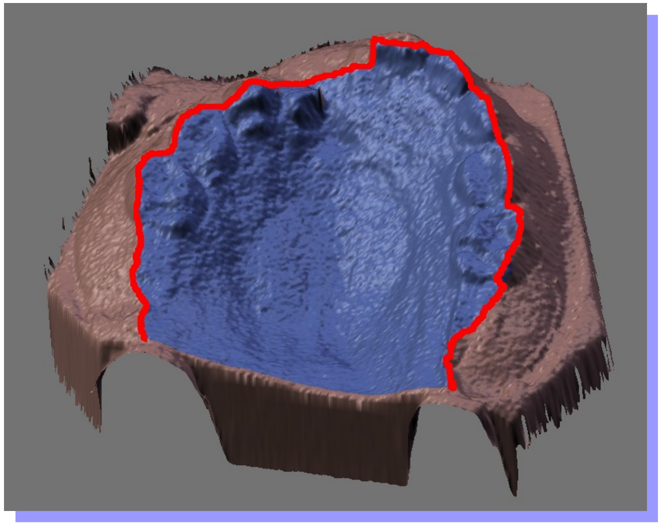


Graph based methods

- Dijkstra shortest path algorithm
  - Limited to 2D data
  - Path between two points locally separating two regions
    - Does not separate two regions in the image
    - In polar space it does
  - Graph (V,E)
    - V pixels
    - E between adjacent pixels (4-, 8- adjacency)
  - Weight of edges depends on application
  - Heuristics (A* algorithm)
- Dynamic programming

Dijkstra shortest path

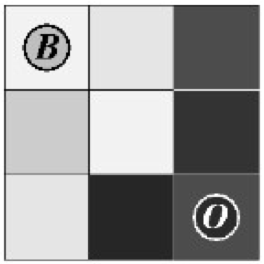




Graph based methods

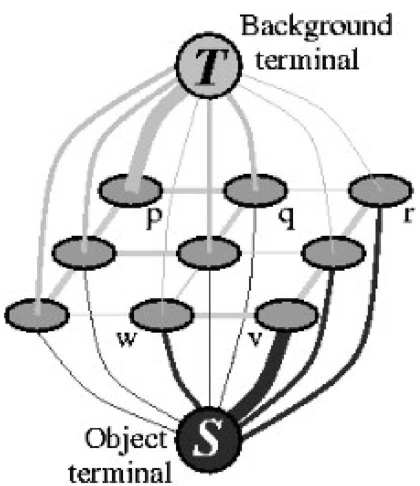
- Graph cut
  - Partition of the graph into two sets
  - Minimum cut
    - sum of edge weights between partitions is minimum
  - Virtual sink & source connected to each image element
  - Minimum cut algorithm finds partitioning (segmentation)
    - Depends on weights of edges (application dependent – intensity, color, position, motion, fit into intensity model)
  - Partitioning into multiple segments is possible
  - Arbitrary dimension

Graph cut



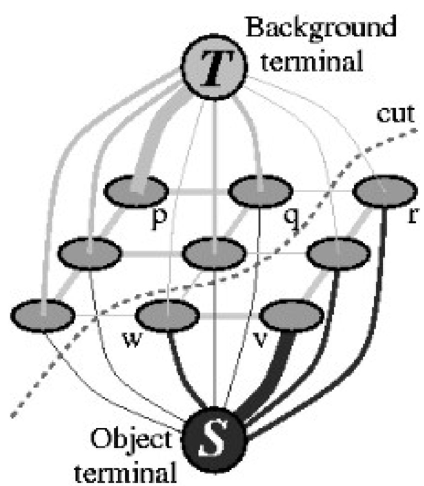
(a) Image with seeds.

⇓



(b) Graph.

⇒



(c) Cut.

⇑

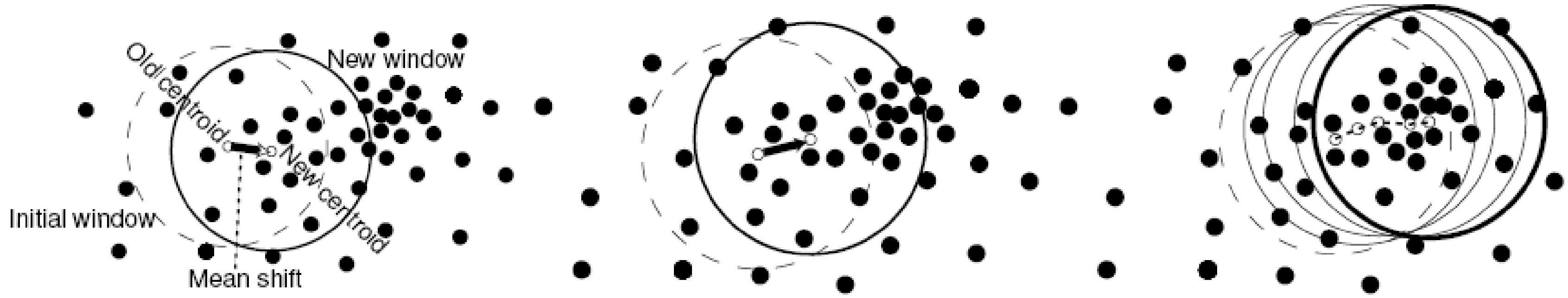
(d) Segmentation results.

Clustering

- Clusters are regions of segmentation
- Clusters are sets of pixels with the same properties (position, color)
- K – means clustering
  1) Cluster centers initialization – random/heuristic
  2) Assign each pixel to cluster minimizing variance
  3) Recompute cluster centers
  4) Repeat from point 2) until center positions change
- Lloyd's algorithm
  - Replace minimizing variance with minimizing distance

Mean shift

- Cluster analysis method
- Each member of a data cloud undergone iterative procedure → shifting to certain point of convergence
- All points shifting to one point of convergence belong to the same cluster (region of segmentation)



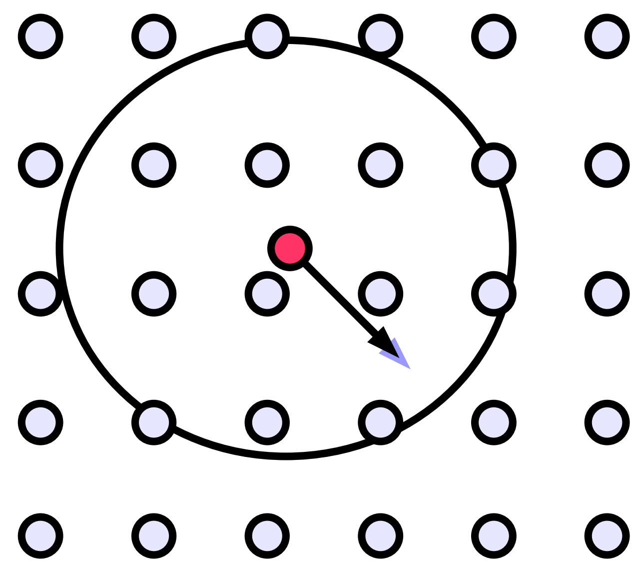
Mean shift - algorithm

- For each pixel → x_0
  - Until converged

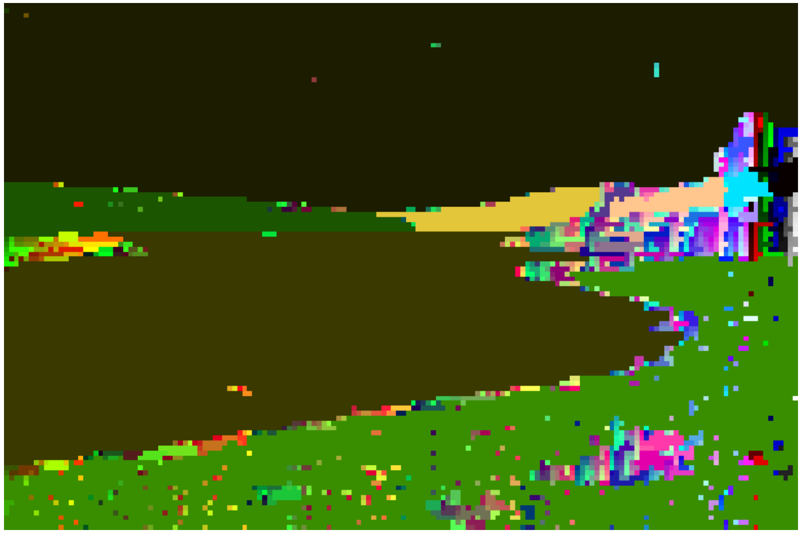
$$x_{i+1} = x_i + \nabla f(x_i) \qquad f(x_i) = \frac{1}{nh_d} \sum_{y \in I} K\left(\frac{y - x_i}{h}\right)$$

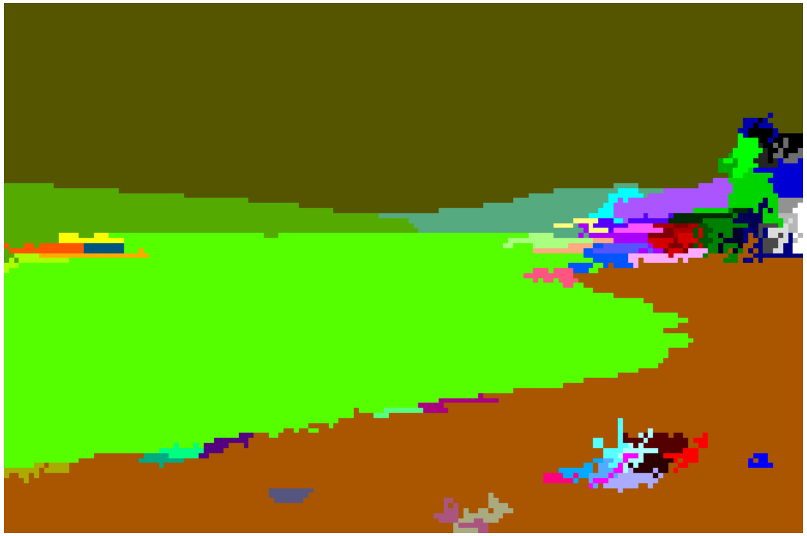
$$i = i + 1$$

- Merge pixels which are close
  - Under certain threshold
- Remove small regions



Mean shift - examples



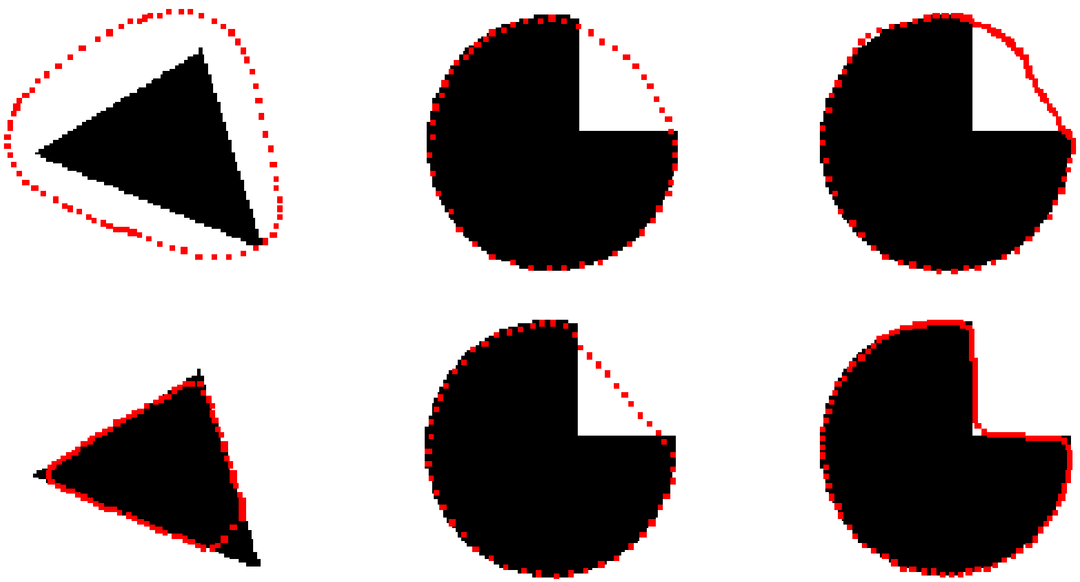


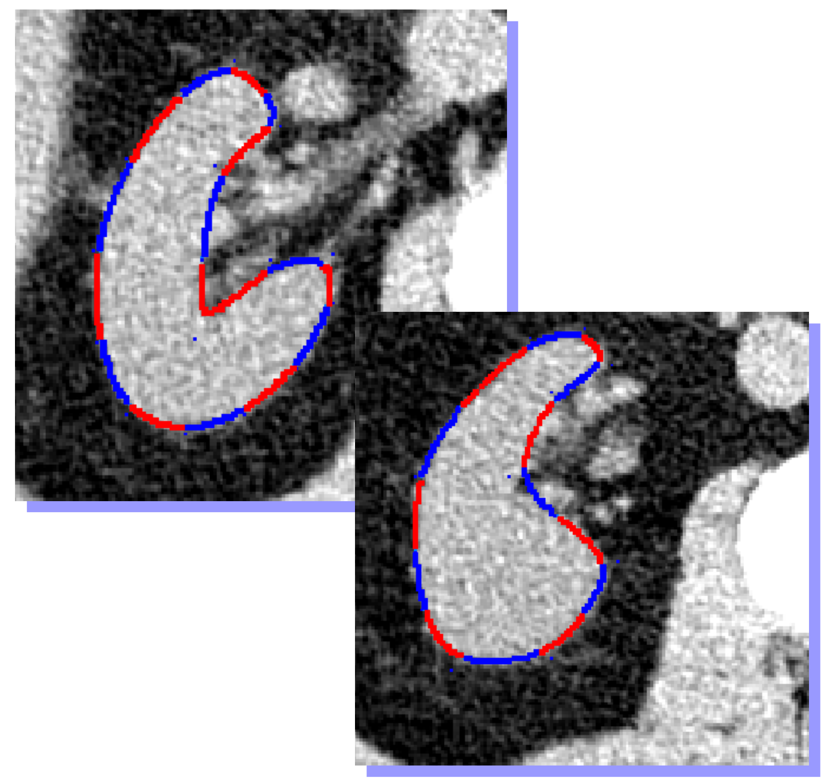
Active models

- *“Optimization of relation between geometrical representation of shape and sensed image”*
- Relation
  - Characteristics – edges, region intensity
- Representation
  - Curves, Planes, Binary masks, Hypersurface
- Optimization
  - Numerical method of finding function minimum

Active contours - snakes

- Generally for 2D data
  - Extendable to 3D via surfaces or slice-by-slice
- Optimization of (closed) curve to fit an object the best
  - Initial position - close to result, inside/outside result
  - Interactivity





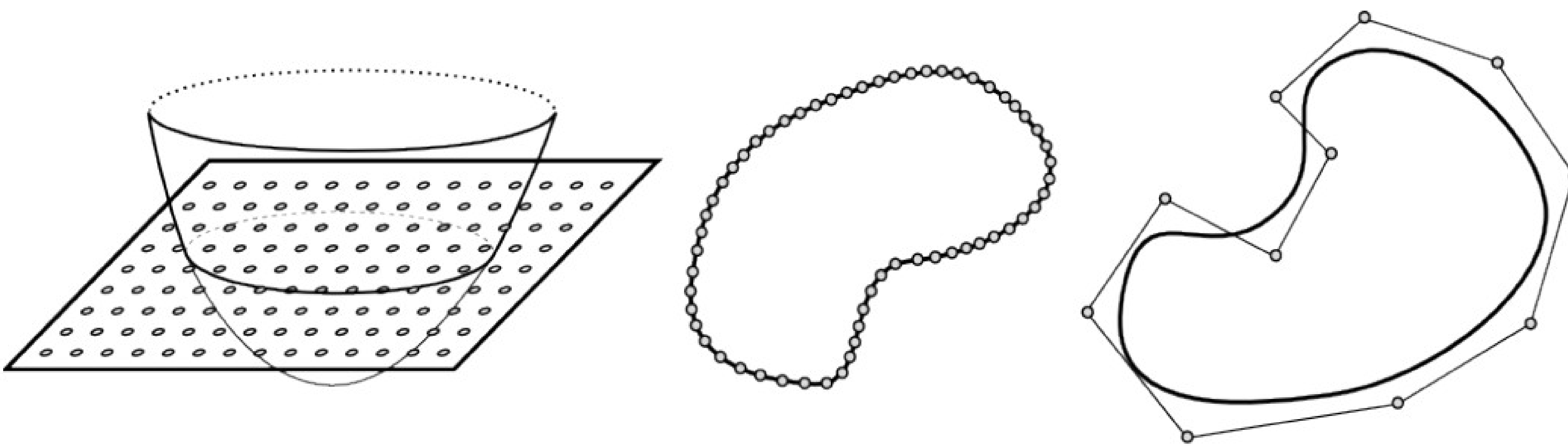
Active contours - snakes

- Various criteria (parametrized by contour)
  - Edges
  - Smoothness
  - Area homogeneity

$$E_{edge}(v) = \int_0^1 |\nabla I(v(t))| dt$$

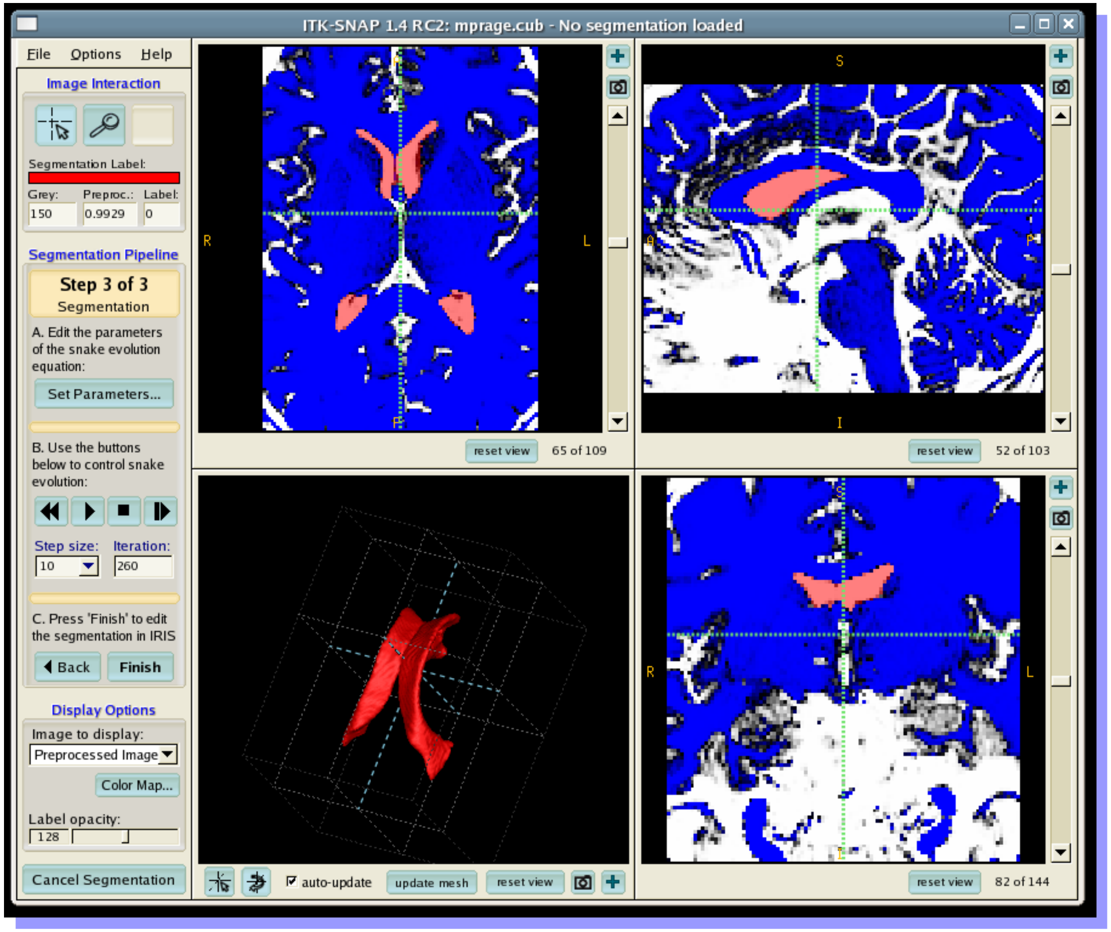
$$E(v) = E_{edge}(v) + E_{smoothness}(v)$$

- Various contour representations



Active contours - snakes

- Various extensions
  - Balloon force
  - Vector flow
  - Geodesic contours
- ITK – SNAP
  - Software
  - Experimental



Level sets

- A set of points induced by real valued function

$$v = L_c = \{(x_{1,} x_{2,} \ldots, x_n) \mid f(x_{1,} x_{2,} \ldots, x_n) = c\}$$

- Other application
  - Shape representation for active models segmentation
  - Fluid simulations, PDE solution, Implicit surfaces
- Pros
  - Arbitrary dimension (2D, 3D, 4D), topology
- Cons
  - Slow, but easily parallelizable

Basic level sets segmentation

- Initialization
  - Regular shape (circle, sphere), user input
  - Construction of a level set
- Until converged
  - For each grid point x_0

$$f_t(x) = f_{t-1}(x) + \frac{\partial f(x)}{\partial t} \quad \Longleftrightarrow \quad c_t(x) = c_{t-1}(x) + \frac{\partial c(x)}{\partial t}$$

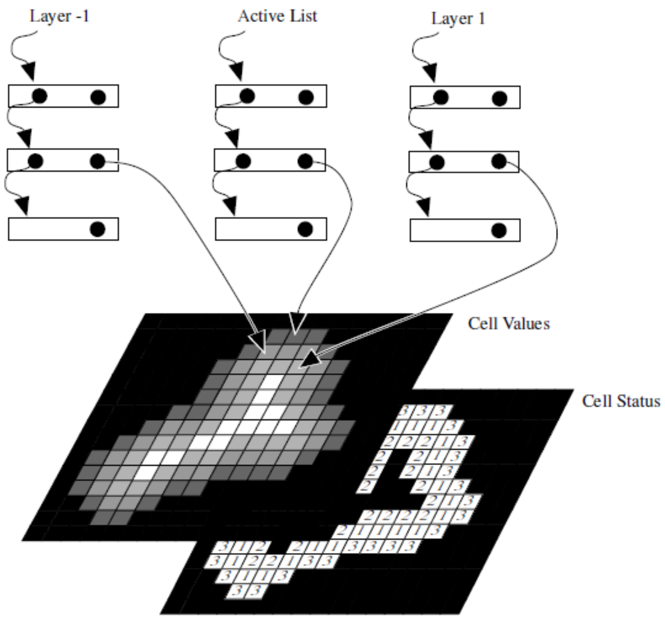
$$\frac{\partial f(x)}{\partial t} = F(x)\left|\nabla f(x)\right|$$

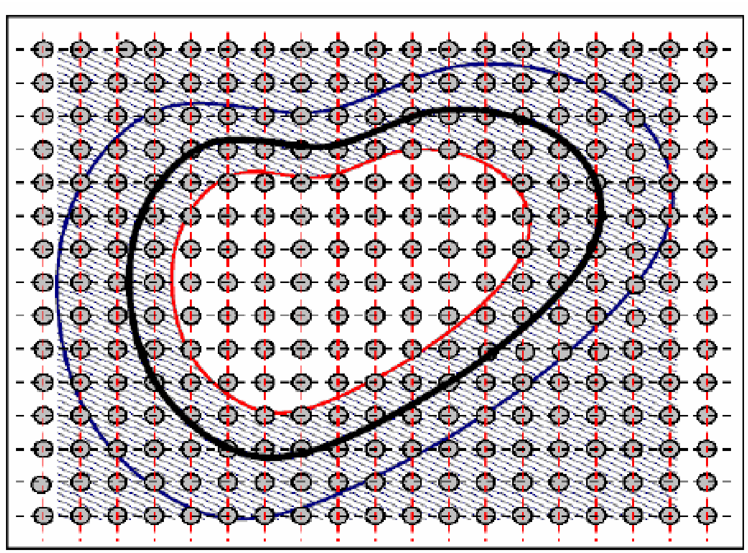
$$F(x) = F_{balloon} + F_{curv} + F_{region}$$

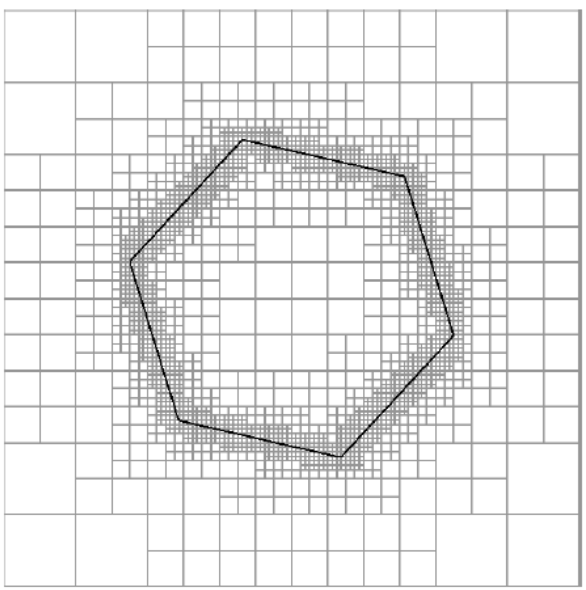
- Reconstruct curve(s) c

Level set speed up techniques

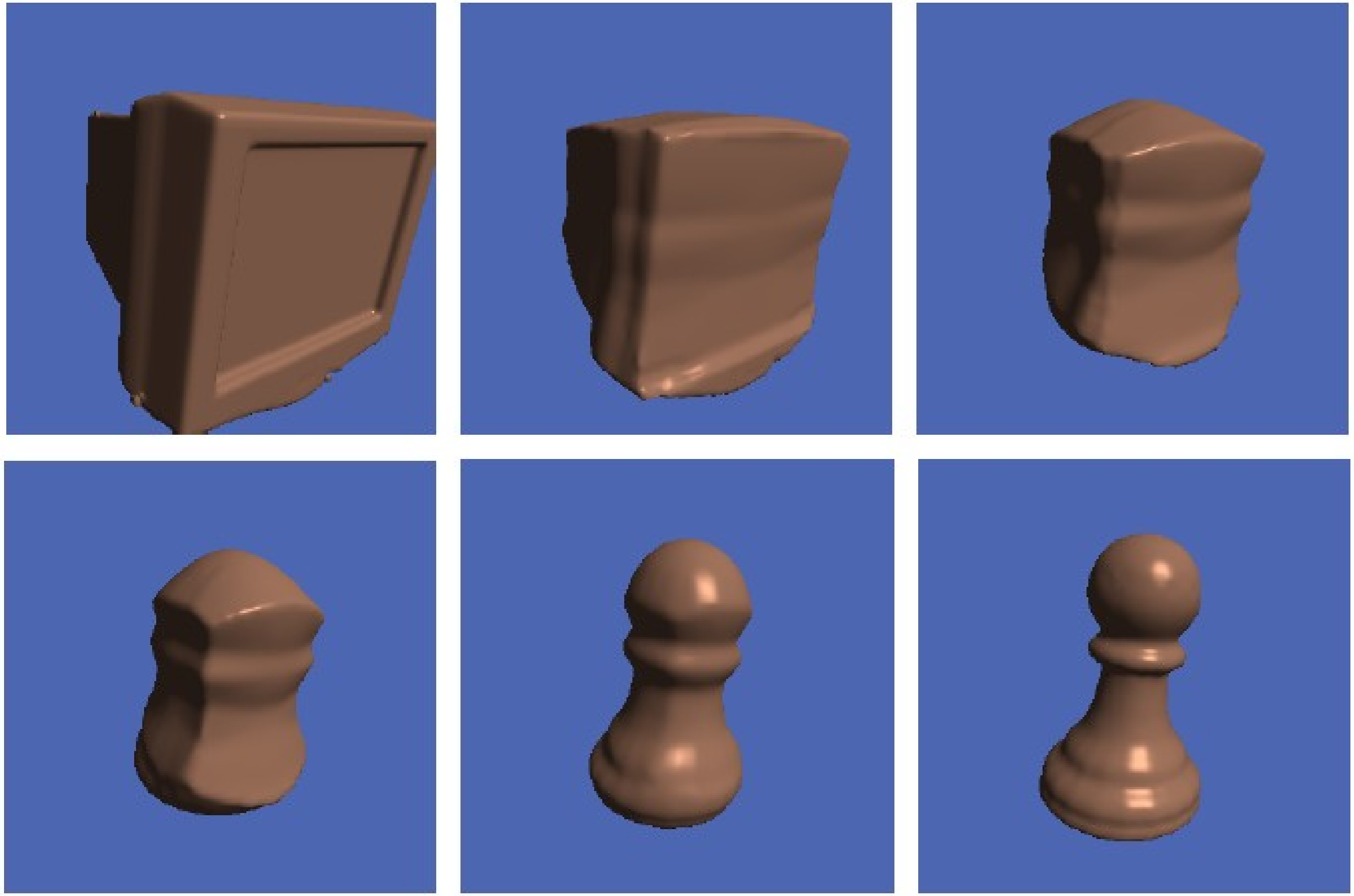
- Narrow band
- Fast marching front
- Sparse fields
- Octree
- Distance transform





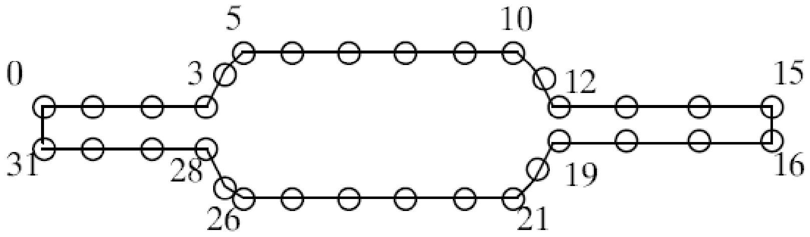


Off topic – Level set morphing



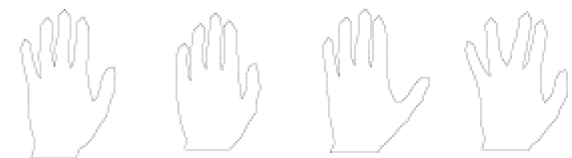
Active shape

- Prior information incorporated into active models
  - Shape
- Two phases
  - Model construction/learning from training set
  - Segmentation – model fitting to data
- Shape representation
  - PDM

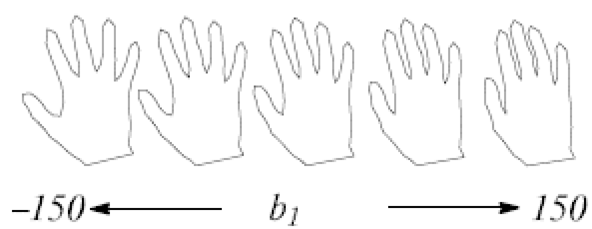


Active shape - learning phase

- Set of examples
  - Big enough, distributed well



- Alignment - registration
- Mean shape
- PCA
  - Covariance matrix, eigenvectors, eigenvalues



- Model

$$shape = meanshape + \sum b_i component_i$$

Active shape - segmentation phase

- Optimize shape and position parameters
  - Minimizing criterion

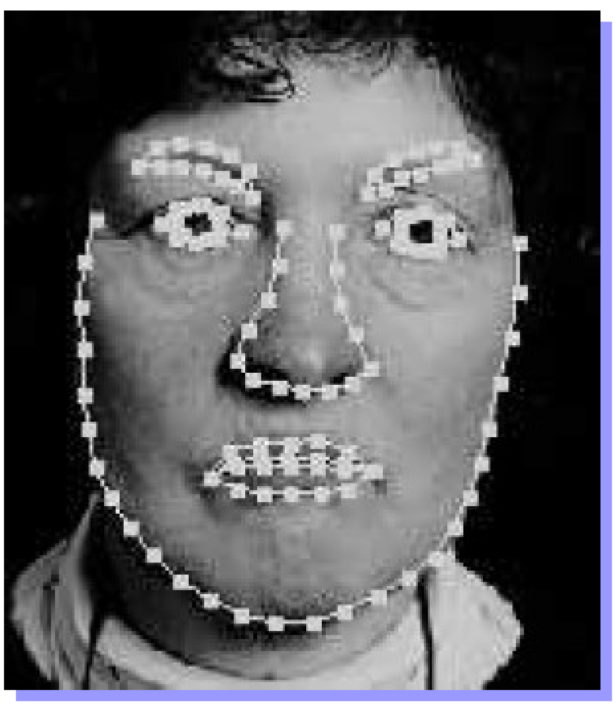
$$E_{fit}(a,b)=S(I,T_a(m+\sum b_i c_i))$$

- Strategy of minimization depends on application
  - Edge guided
  - Genetic approach
  - Numerical optimization

$$E_{fit}^{k+1}(a,b)=E_{fit}^{k}(a,b)+\nabla_{a,b}E_{fit}^{k}$$

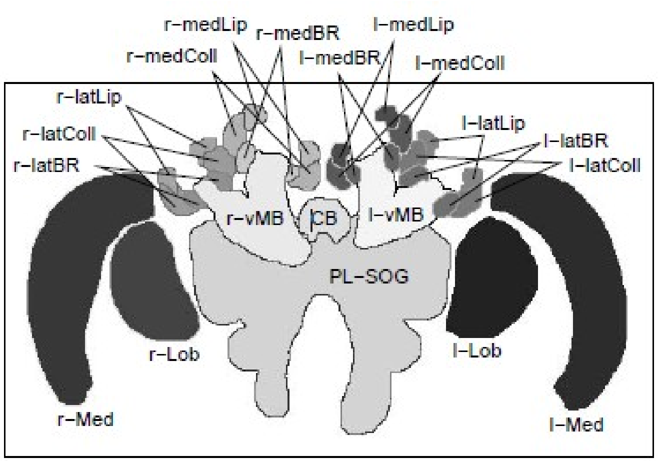
Active appearance

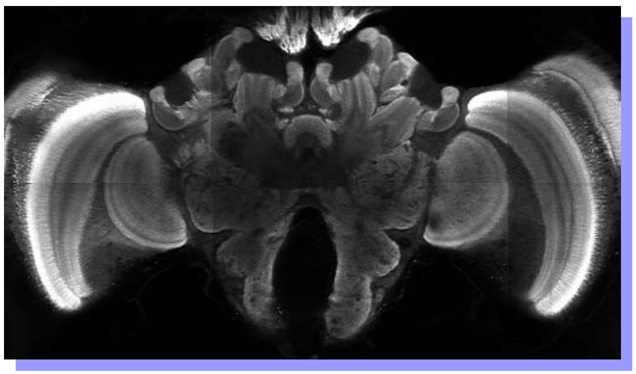
- Shape and intensity prior information active models
  - Intensity profiles along the contours – mean profiles
  - Intensity of the whole image – mean image

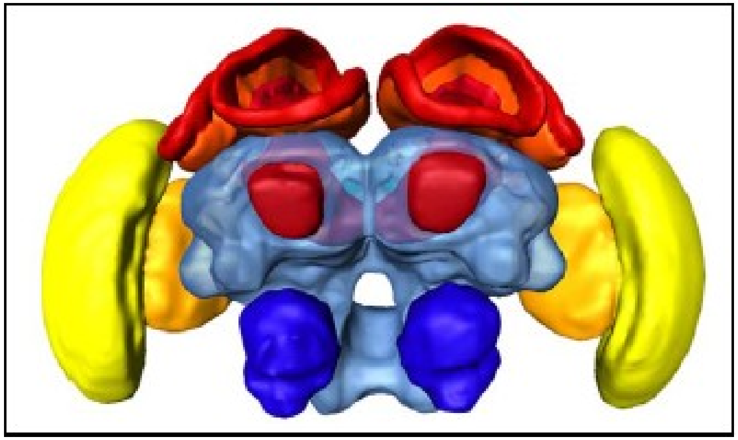


Atlas-based segmentation

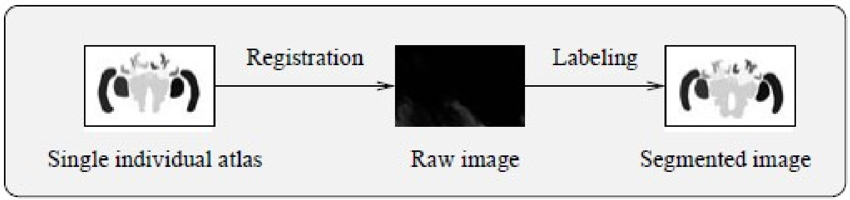
- Shape, intensity, spatial relations, ... priori information
- Loosing ability to segment extreme cases
  - Pathological subjects
- Registration of atlas (labeled) subject to segmented
  - Corresponding elements induce segmentation



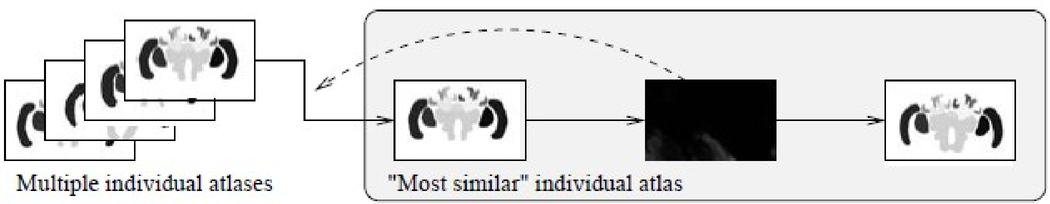




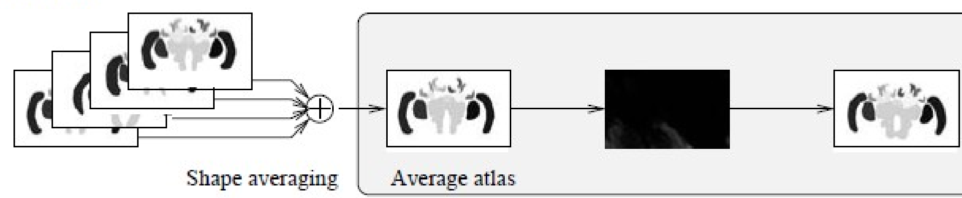
Atlas-based approaches



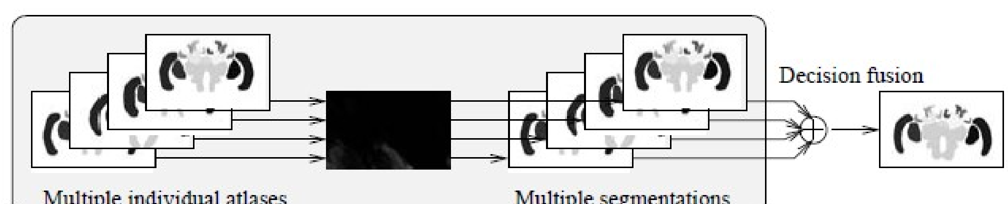
IND: Segmentation using a single individual atlas.



SIM: Segmentation using the “most similar” individual atlas.



AVG: Segmentation using an average shape atlas.



MUL: Independent segmentation using multiple individual atlases with decision fusion.

Conclusion

- Good segmentation algorithm is
  - Robust
  - Fast (useful)
  - Precise
- Good segmentation way
  - Combination of several methods
  - Incorporation of prior information
- Implementation
  - MedV4D interface to ITK (segmentation and registration algorithms)

Q & A

References

- Pham et al., A survey of current methods in medical image segmentation, 1998
- Sarang Lakare, 3D Segmentation Techniques for Medical Volumes, 2000
- S. Fiorentini et al., A Simple 3D image segmentation technique over Medical Data, 2001
- R. Pohle, K. Toennies, A New Approach for Model-Based Adaptive Region Growing in Medical Image Analysis, 2001
- J. S. Suri et al., Quo Vadis, Atlas-Based Segmentation?, 2005
- Sezgin, Sagur, Survey over thresholding techniques and quantitative performance evaluation, 2004
- Kass et al., Snakes – Active contours, 1987

References

- Malladi et al., Shape Modeling with Front Propagation: A Level Set Approach, 1995
- Cootes,Taylor, Active Shape Models – Smart Snake, 1992
- Cootes et al., Active Appearance Models, 1998
- Wu, Leahy, An optimal graph theoretic approach to data clustering: theory andits application to image segmentation, 1993
- Gonzalez, Woods, Digital Image Processing, 3rd Edition, Pearson Prentice Hall 2008, p. 689-794
- T.S. Yoo, Insight into images: Principles and Practice for Segmentation, Registration, and Image Analysis, AK Peters 2004, p. 119-230